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Multiwavelength Distributed Feed Back Laser Array Transmitters for Optical Network Technology Consortium Reconfigurable Optical Network Testbed

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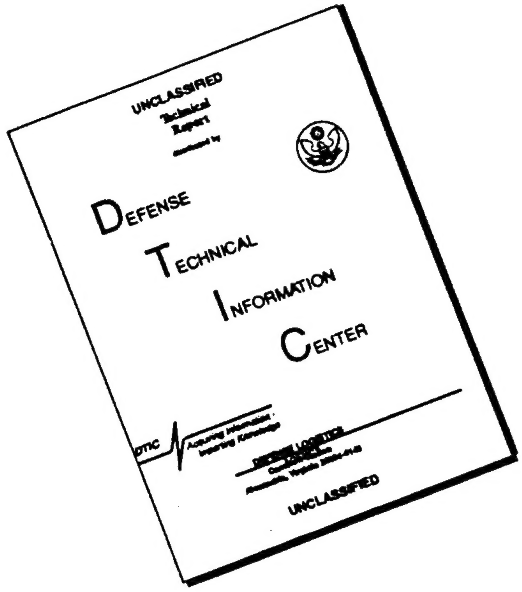

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13. ABSTRACT *(Maximum 200 words)*

We discuss the design, fabrication, and performance of multiwavelength laser array transmitters that have been used in the reconfigurable optical network testbed for the Optical Network Technology Consortium (ONTC). The experimental 4-node multiwavelength network testbed is SONET/ATM compatible. It has employed multiwavelength DFB laser arrays with 4 nm wavelength spacing for the first time. The testbed has demonstrated that multiwavelength DFB laser arrays are indeed practical and reproducible. For the DFB laser arrays used in such a network the precise wavelength spacing in the array and the absolute wavelength control are the most challenging tasks. We have obtained wavelength accuracy better than ±0.35 nm for all lasers, with some registered to better than ±0.2 nm. We have also studied the array yield of our devices and used wavelength redundancy to improve the array yield. Coupling efficiencies between -2.1 to -4.5 dB for each wavelength channel have been obtained. It is achieved by using specially designed lensed fiber arrays placed on a silicon V-grooved substrate to exactly match the laser spacing. The transmitter consisted of a multichip module containing a DFB laser array, an 8-channel driver array based on GaAs ICs, and associated RF circuitry.

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ACRONYMS

ARPA	Advanced Research Projects Agency
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
DFB	Distributed Feed Back
MOCVD	Metal Organic Chemical Vapor Deposition
OEIC	Opto Electronic Integrated Circuit
ONTC	Optical Network Technology Consortium
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TEC	Thermal electric cooler
TDM	Time division multiplexing
WDM	Wavelength division multiplexing

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Abstract— We discuss the design, fabrication, and performance of experimental multiwavelength laser array transmitters that have been used in the reconfigurable optical network testbed for the Optical Network Technology Consortium (ONTC). The experimental four-node multiwavelength network testbed is SONET/ATM compatible. It has employed multiwavelength DFB laser arrays with 4 nm wavelength spacing for the first time. The testbed has demonstrated that multiwavelength DFB laser arrays are indeed practical and reproducible. For the DFB laser arrays used in such a network the precise wavelength spacing in the array and the absolute wavelength control are the most challenging tasks. We have obtained wavelength accuracy better than ±0.35 nm for all lasers, with some registered to better than ±0.2 nm. We have also studied the array yield of our devices and used wavelength redundancy to improve the array yield. Coupling efficiencies between −2.1 to −4.5 dB for each wavelength channel have been obtained. It is achieved by using specially designed lensed fiber arrays placed on a silicon V-grooved substrate to exactly match the laser spacing. The transmitter consisted of a multichip module containing a DFB laser array, an eight-channel driver array based on GaAs IC's, and associated RF circuitry.

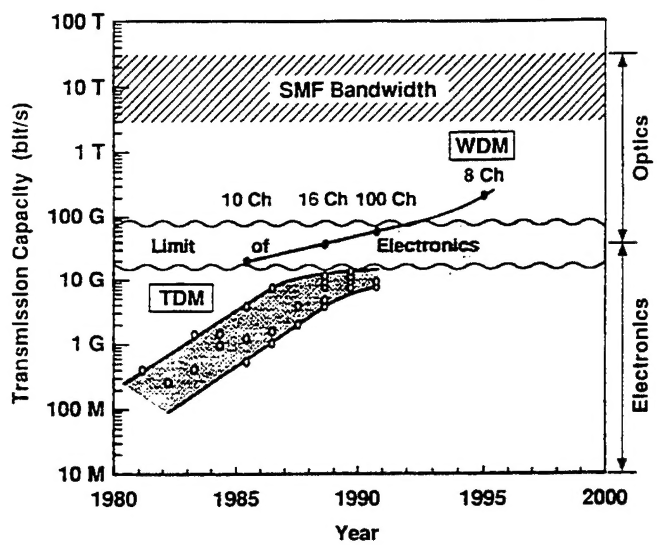


Fig. 1. The trend of transmission capacity of optical fiber communication systems.

I. Introduction

Traditionally, increasing the transmission bandwidth in telecommunications has been accomplished by time-division-multiplexing (TDM) through the increase in the transmission speed. Early commercial systems at rates from 45 Mbit/s to 1.7 Gb/s have been deployed in the US in the last decade. More recently, SONET/SDH OC-48 systems at 2.5 Gb/s have been installed and used worldwide, while OC-192 systems at 10 Gb/s are being tested in several laboratories. Beyond 10 Gb/s, it is believed that wavelength division multiplexing (WDM) is a viable technology to exploit the extremely broad optical bandwidth (30 THz) in the low loss transmission window of the optical fiber. As shown in Fig. 1, for example, early WDM transmission experiments with 10, 16, and 100 wavelength channels with the aggregated capacity of 20, 32, and 62 Gb/s were reported in 1985, 1988, and 1990, respectively [1]–[4]. An eight-channel WDM system with 20 Gb/s per channel was reported in a recent experiment [5]. It is clearly seen that the aggregated transmission capacity using WDM has surpassed that of the traditional TDM systems. By using erbium-doped fiber amplifiers WDM systems can be made cost-effective for certain applications relative to traditional TDM systems with electronic regenerators. For instance, a four-channel WDM system with 10 Gb/s per channel would be cost effective at the present time compared with a 40 Gb/s TDM system. Moreover, the wavelengths add a new functionality that can be used for routing signals and for providing services that are independent of the signal format. These capabilities are specially attractive for optical networking. Recently, several research groups have proposed all optical networks based on WDM technologies [6]–[8]. Fig. 2 shows the concept of a scaleable, modular multiwavelength network with rearrangeable wavelength routing and switchable wavelength conversion [6]. The number of nodes in a scaleable network is weakly dependent on the number of wavelengths used. Scaleability is achieved by wavelength conversion and reuse.

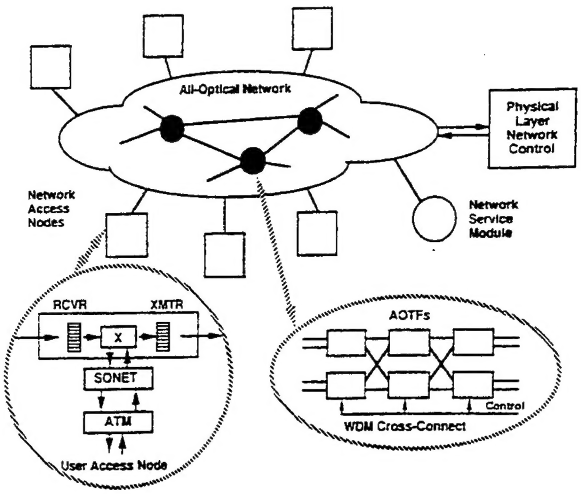


Fig. 2. A scaleable, modular multiwavelength multihop optical network with rearrangeable wavelength routing and switchable wavelength conversion [6].

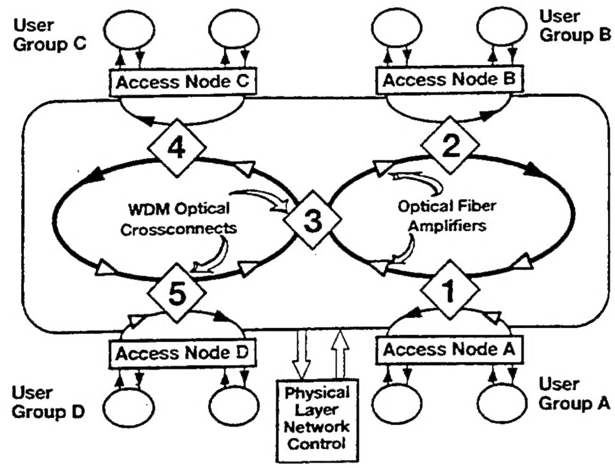


Fig. 3. The architecture of a four-node rearrangeable optical network testbed.

Recently, a four-node testbed in a double ring configuration as shown in Fig. 3 has been constructed and demonstrated by the Optical Network Technology Consortium (ONTC) [9]. The key enabling technologies are InP-based DFB laser arrays and multichannel OEIC receiver arrays at each network access node, and multiwavelength cross-connect switches interconnecting all access nodes in the core of the network. Wavelength conversion on a packet-to-packet basis is accomplished at the access nodes by the ATM switches. Both acousto-optic tunable filters and optical interference filters have been used successfully for wavelength routing.

This paper presents the design, fabrication, and performance of the experimental laser array transmitters used in the ONTC testbed. Special attention is paid to the control of the wavelength accuracy and wavelength channel spacing in the design of the experimental DFB laser array. Improvement of the laser array yield has been obtained by the use of wavelength redundancy. Fiber array coupling employing silicon V-grooves as well as thermal management of the transmitter module further assure adequate power output into the fibers and long term stability of the operating wavelengths.

II. Multiwavelength DFB/DBR Laser Arrays

A. Laser Array Overview

Multiwavelength DFB/DBR laser arrays have been demonstrated in the 1.3 μm wavelength region [10] and in the 1.55-μm wavelength region [11]–[20]. A DFB laser array, with up to 21 wavelengths, integrated with a star coupler and optical amplifiers [16] has been achieved in the 1.55 μm region. A similar DBR laser array integrated with electroabsorption modulators has also been reported [19]. Table I summarizes the recent progress of multiwavelength laser arrays. In general, the lasing wavelength of each laser in an array coincides with the Bragg wavelength λ_o of the grating given by [21]

$$\lambda_o = 2n_{\text{eff}}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the waveguide and the grating spatial period. To obtain multiple wavelengths in an array, the grating pitches for individual lasers are varied on the wafer during the grating fabrication by one of the following techniques: 1) stepping a window mask during multiple holographic exposures [10], [19], 2) e-beam direct writing [14]–[16], 3) exposing an e-beam-generated grating mask with X-ray [12], and (4) exposing an e-beam-generated phase grating mask with UV light (near field holographic printing) [22]. An alternative way is to use a fixed-pitch grating and to change the effective refractive index of the waveguides within an array. This is accomplished by producing different thickness in the waveguide cores using multiple selective etching [11] or selective area growth [20]. The thickness is controlled by several thin stop-etch layers during etching [11] or by the area of the mask during growth. Among the techniques mentioned above, near-field holographic printing of gratings onto the wafers seems to be the most attractive way for potentially low-cost production. It is a batch process and compatible with the current photolithography process used in the laser fabrication.

To assure lasing at each Bragg wavelength in a DFB laser array, $\lambda/4$-shifted gratings are incorporated and the facet reflections are eliminated by anti-reflection coatings or slanting the rear facet [10], [12], [14]–[16]. Wavelength spacings as small as 0.66 nm [12] and as large as 7 nm [14] have been reported. The maximum wavelength span is limited by the optical gain bandwidth of the active layer. The largest span of 131 nm was obtained by the use of compressive-strained multiple quantum well active layers [14]. The lasing wavelengths range from 1459.2 to 1590.6 nm. which is considerably wider than the optical bandwidth of erbium-doped fiber amplifiers (1535–1565 nm). DBR laser arrays have the advantage of being tuned to a precise wavelength spacing or a variable wavelength spacing that is required by the network [11], [13], [18]–[20]. However, active wavelength monitoring and feedback control are required since the tuning characteristics may change with aging [23]. In contrast. the lasing wavelength of a DFB laser module has been shown to be very stable (−0.01 nm/yr.) [24]. Therefore, it is desirable

TABLE I

SUMMARY OF THE RECENT PROGRESS OF MULTIWAVELENGTH LASER ARRAYS

	Year	# of λs	Structure	Active Layer	Grating	Spacing/Span nm	Ref.
Toshiba	1987	5	DFB	Bulk (1.3 μm)	Holography[1]	5/20	10
AT&T	1989	4[3]	DBR	MQW	Holography[2]	Tunable/10-20	11
NTT	1990	20	DFB	Bulk	EB/x-ray	0.66/12.5 1/19	12
NEC	1990	4[3]	DBR	MQW	Holography	Tunable/8	13
Bellcore	1992	20	DFB	CSMQW	EB	7/131	14
Bellcore	1992	20	DFB	TSMQW	EB	3/55	15
Bellcore	1992	21[3]	DFB	CSMQW	EB	3.7/75	16
NTT	1992	10	DFB	CSMQW	EB	Tunable/2	17
AT&T	1993	8	DBR	CSMQW	EB/UV	0.8/tunable	18
AT&T	1993	16[3]	DBR	CSMQW	Holography[1]	0.67/tunable	19
Oki	1993	4	DBR	MQW	Holography[2]	5/15	20

[1] Stepping a window mask during repeated exposures.

[2] Different waveguide core thickness

[3] With integrated wavelength combiners and optical amplifiers.

[4] DFB: distributed-feedback, DBR: distributed Bragg reflector, MQW: multiple quantum well,

CS: compressive-strained, TS: tensile-strained, EB: electron beam.

to use fixed multiwavelength DFB laser arrays without active wavelength control if the required wavelength spacing must be reproducible within the manufacturing tolerance.

B. Control of Wavelength Spacing [30]

To use the multiwavelength laser array in real systems, its wavelength spacing has to match the network specification within the tolerance given by the optical bandwidth of wavelength-selective devices such as filters and multiplexers/demultiplexers. With a constant wavelength spacing, the wavelength comb generated by the laser array can then be moved as a group by adjusting the heat sink temperature to match the wavelength comb used in the system. The lasing wavelength of a DFB laser red-shifts at a rate of $\sim$1 Å/°C (12.5 GHz/°C at 1.55 μm wavelength region) resulting from the temperature dependence of the waveguide effective refractive index. Therefore, the practicality of the multiwavelength laser arrays depends on how well the wavelength spacing can be controlled during fabrication.

The Bragg wavelength spacing $\Delta\lambda$ between the neighboring wavelengths within a DFB/DBR laser array is mainly determined by the effective refractive index n_{eff} and the increment $\Delta\lambda$ in the grating periods:

$$\Delta\lambda = \frac{2n_{\text{eff}}\Delta\Lambda}{1+D} + \delta\lambda \tag{2}$$

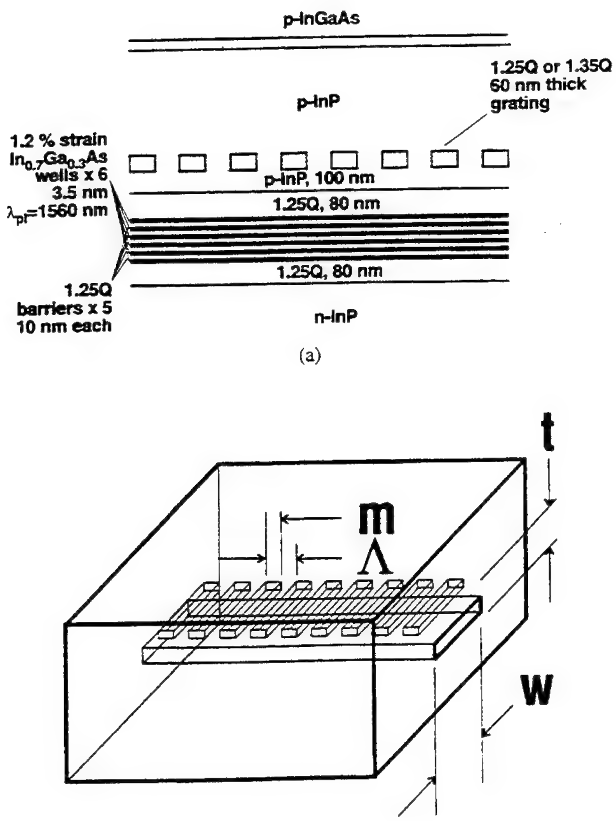
$$D = -\frac{\lambda}{n_{\text{eff}}}\frac{\partial n_{\text{eff}}}{\delta\lambda} \tag{3}$$

where the parameter D is used to take into account the wavelength dispersion of the material and waveguide, and $\delta\lambda$ is the error in wavelength spacing given by

$$\delta\lambda = \frac{2n_{\text{eff}}\delta\Lambda + \dfrac{\lambda}{n_{\text{eff}}}\dfrac{\partial n_{\text{eff}}}{\partial x}\delta x}{1+D} \tag{4}$$

where $\delta\Lambda$ is the fabrication error in grating pitch (digitizing error $\sim$0.04 Å in our e-beam writer), and δx represents the relative random fluctuations that cause the effective refractive index to vary among different lasers within an array. To obtain a uniform wavelength spacing, we have to minimize $\delta\Lambda$ and δx. We have estimated the wavelength variation due to imperfections in grating and waveguide fabrication using the layer structure shown in Fig. 4. The lateral confinement is assumed to be buried heterostructure. An InP buffer layer is inserted between the grating layer and the multiple quantum well active layer such that the grating depth is accurately controlled by the growth instead of by chemical etching [25]. The Bragg wavelength is assumed to be 1552 nm. The effective refractive index is determined from the eigenfunction of the multilayer waveguide constructed using the matrix method [26] and solved by Muller's method [27] using the material refractive index published in [28]. The first two rows of Table II list the derivatives of the effective refractive index (or the Bragg wavelength) with respect to the possible fluctuations. δx includes the grating parameter [mark to period ratio m/Λ shown in Fig. 4(b)] and the waveguide parameters (width W, bandgap wavelength λg and normalized thickness t/t_0). The last three rows show the allowed relative fluctuations on grating and waveguide parameters to achieve wavelength spacing variations less than 0.2 nm or 0.5 nm. There are other factors affecting the Bragg wavelength through carrier density fluctuation such as laser threshold current and longitudinal spatial hole burning. In general, they are not as critical as imperfections in fabrication especially if quantum well active layers are used [29].

We have characterized eight 21 wavelength laser array chips (129 DFB lasers) from one MOCVD grown wafer previously made in our laboratory. A few lasers on the chip are not included because of high threshold current or lasing in dual modes due to the imperfection in fabrication. For each array chip, the wavelength spacing $\Delta\lambda$ is determined by a least-mean-square fit to the wavelengths measured at 20 mA above threshold, and then the wavelength deviation $\delta\lambda$ from the line of constant wavelength spacing is estimated for each channel. As shown in Table III, the wavelength spacing of each chip is measured to be within 3.71 $\pm$ 0.05 nm. The absolute wavelength is about 2 nm away from the calculated value due to uncertainties in the exact parameters of growth and fabrication in spite of locally good uniformity. Our experimental data also indicate that any one of the DFB lasers in an array has about a 35% probability to lase within 0.2 nm of the wavelength demanded by the constant wavelength spacing. The probability increases to 74% if the wavelength tolerance is relaxed to 0.5 nm. The above yield does not take into account other specifications such as threshold current and power. However, the yield could be improved in a production environment because of tighter control in the material properties and the fabrication process.



(a)

(b)

Fig. 4. DFB laser layer structure used to calculate the Bragg wavelength variations induced by the fabrication imperfections in gratings and waveguides, (a) longitudinal cross section and (b) schematic drawing. 1.25Q: GaInAsP quaternary with a bandgap wavelength of 1.25 μ mW: waveguide width, t: waveguide thickness, Λ: grating period and m: mark portion of the grating.

TABLE II
WAVELENGTH VARIATION OF DFB LASERS DUE TO IMPERFECTIONS IN FABRICATION

	δx					
	δΛ, Å	δm/Λ, %	δW[1], μm	δW[2], μm	$\delta\lambda_g$, nm	$\delta t/t_o$, %
$\frac{\partial n_{eff}}{\partial x}$	-	9.05×10^{-5}	1.34×10^{-2}	7.91×10^{-3}	1.76×10^{-4}	6.16×10^{-4}
$\frac{\partial \lambda_0}{\partial x}$	0.585	0.04	5.93	3.49	0.0776	0.272
δλ<0.2 nm	<0.34	<5	<0.034	<0.057	<2.58	<0.74
δλ<0.5 nm	<0.885	<12.5	<0.085	<0.144	<6.45	<1 84
δλ<1 nm	<1.71	<25	<0.169	<0.287	<12 9	<3.68

[1] 1.5 μm wide waveguide

[2] 2 μm wide waveguide

[3] $\frac{\partial \tilde{n}_{eff}}{\partial \lambda}=-1.99\times10^{-4}$/nm and D=0.0962

[4] λ_0 = 1552 nm

C. DFB Laser Array Yield [30]

Since all the wavelengths in an array have to fall within the range allowed by the optical bandwidth of the wavelength selective devices in the networks, the array yield may drop significantly when the number of wavelengths increases. The array yield could be improved by assigning more than one laser per wavelength. Table IV shows the fixed wavelength DFB laser array yield estimated from the measured yield of a single DFB laser discussed in the previous section. The array yield y_a is calculated as follows:

$$y_a = 1 - (1 - y_1^r)^n \tag{5}$$

where y_1 is the yield of a laser with its lasing wavelength within the allowed wavelength tolerance, r is the number of lasers per wavelength (wavelength redundancy), and n is the number of wavelengths in an array. One can see that wavelength redundancy significantly increases the array yield. With two DFB lasers per wavelength, we can expect a reasonable array yield (>50%) up to 8 wavelengths if the allowable wavelength tolerance is greater than ±0.5 nm. It seems that it is difficult to obtain a good array yield with the fixed wavelength approach if the tolerance is reduced to less than ±0.2 nm without improving the uniformity in growth and fabrication. Therefore, the networks which require very tight wavelength tolerance (<0.2 nm) probably have to rely on tunable laser arrays together with an active feedback wavelength control.

TABLE III
MEASURED WAVELENGTH VARIATION OF DFB LASER ARRAYS

Dev. #	# of λs	λ_{12}[1] nm	$\delta\lambda_{12}$[2] nm	$\Delta\lambda$[3] nm	$\sigma_{\delta\lambda}$[5] nm	δλ[4]<0.2 nm # (%)	δλ<0.5 nm # (%)	δλ<1 nm # (%)
Cal.		1544.99		3 63				
11	14	1544	-0.99	3.76	0.31	5 (36)	13 (93)	14 (100)
15	10	1541.6	-3.39	3.72	0.42	2 (20)	5 (50)	8 (80)
24	18	1543.1	-1.89	3.72	0.38	8 (44)	13 (72)	17 (94)
26	13	1545 7	0.69	3.66	0 49	3 (23)	8 (62)	12 (92)
51	17	1542.8	-2 19	3.68	0.3	6 (35)	14 (82)	16 (94)
56	19	1542 7	-2.29	3.71	0.53	7 (37)	14 (74)	17 (89)
57	17	1542 8	-2.19	3.74	0.23	7 (41)	14 (82)	15 (88)
58	21	1542.6	-2.39	3.72	0.35	7 (33)	15 (71)	18 (86)
Average	16	1542.8	-2.19	3.72±.05	0.38			
Total	129					45 (35)	94 (74)	117 (91)

[1] λ_{12}: measured wavelength for DFB laser 12 in a 21-wavelength DFB laser array.

[2] $\delta\lambda_{12} = \lambda_{12}$ - calculated wavelength (1544 99 nm)

[3] Δλ: average wavelength spacing within a 21-wavelength DFB laser array

[4] δλ: measured wavelength deviation away from the average constant wavelength spacing

[5] $\sigma_{\delta\lambda}$: standard deviation of δλ within an array

TABLE IV
FIXED WAVELENGTH DFB LASER ARRAY YIELD ESTIMATED FROM THE YIELD OF A SINGLE DFB LASER OBTAINED FROM OUR INTEGRATED CHIPS

	δλ < ±0.2 nm		δλ < ±0.5 nm	
	1 LD/λ	2 LD/λ	1 LD/λ	2 LD/λ
1 λ	35 %	58 %	74 %	93 %
4 λs	1.5 %	11 %	30 %	76 %
8 λs	0.02 %	1.2 %	9 %	57 %
16 λs			0.8 %	33 %

D. Laser Array Fabrication

The linear laser array contains 20 DFB lasers with two lasers operating at the same wavelength to produce ten wavelength channels from 1542 to 1560 nm with 2 nm spacing. Each laser has a modulation bandwidth greater than 3 GHz. However,

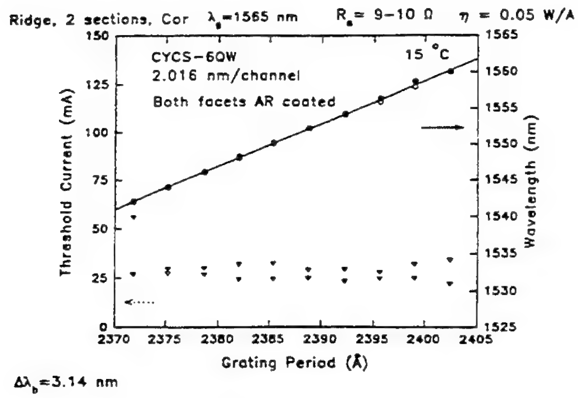


Fig. 5. Lasing wavelengths and threshold currents of a mutiwavelength DFB laser array as a function of grating period under CW operation.

in the testbed implementation, only four wavelength channels spaced 4 nm apart are used, with each wavelength channel operated at 155 Mb/s, dictated by the speed of the commercial ATM switches. The built-in wavelength redundancy on the chip helps to improve the array yield as well as its reliability.

The wafer is grown by low pressure metal organic chemical vapor deposition (LP-MOCVD) at 625 °C and 76 torr. The active layer consists of six compressively strained $Ga_{0.17}In_{0.83}As_{0.73}P_{0.27}$ quantum wells. The well thickness is 8 nm. The barrier layers are $Ga_{0.375}In_{0.625}As_{0.73}P_{0.27}$ that is tensile strained to compensate the compressively strained active layers.

On each wafer, ten $\lambda/4$-shifted first-order gratings with different periods are generated by fast *e*-beam lithography. The gratings are etched into the upper part of the waveguide region by reactive ion etching using a noncorrosive gas mixture of CH_4/H_2. The ridge-waveguide lasers are formed by a self-aligned process. Each chip contains 20 lasers divided into two groups of ten. The first group produces 10 wavelengths with 2 nm spacing between adjacent lasers of 250 μm physical separation. Identical wavelengths are reproduced in the second group for wavelength redundancy. The lasers are cleaved into 500 μm long cavities, and antireflection coatings are applied to both facets to assure single-longitudinal-mode operation.

The built-in wavelength redundancy in the array design, the uniform growth by MOCVD, and the precision of *e*-beam gratings have all contributed to the achievement of the wavelength accuracy required for the multiwavelength laser array.

E. Laser Array Performance

The lasing wavelengths and threshold currents of a typical laser array are shown in Fig. 5. The array shows a 10 wavelength comb of 2 nm spacing as designed. The light horizontal lines indicate the four designated wavelengths (1546, 1550, 1554, and 1558 nm) for the ONTC testbed. The wavelength deviations from the designated channel wavelengths are less than 0.35 nm for all wavelength channels. The side-mode suppression ratio is 35 dB or better for all wavelengths. Each laser delivers a minimum of 2 mW facet power at a drive current of 60 mA.

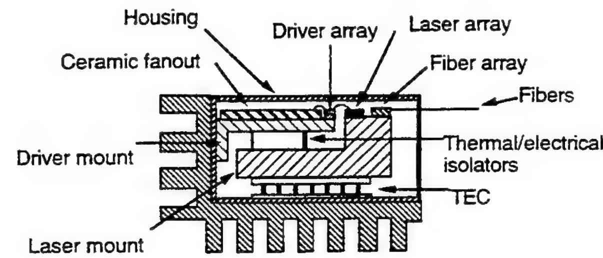


Fig. 6. Schematic representation of laser array transmitter module.

III. Array Transmitter Module

A. Module Design

The physical design features of the module are schematically represented in a cross-sectional view as shown in Fig. 6. The package contains a die-attached laser array and a fiber array, which has been actively aligned (lasers active) to the laser array. Fig. 7 shows a micrograph of the fiber array aligned with the laser array by using a silicon V-grooved substrate that is precisely matched to the laser spacing. The fiber array consists of low reflectance conical microlenses [31] that we have designed and fabricated. The conical microlenses were fabricated on geometrically concentric fibers with essentially identical outside diameters. This step was essential in using preferentially etched silicon V-grooved substrates to fabricate dimensionally precise fiber arrays.

In assembling the module, the laser array is mounted (soldered) onto a gold-plated copper submount. The laser submount is thermally and electrically isolated from the metallic submount on which the driver chip is mounted. A custom chip carrier (electrical fanout) is also mounted on the same submount as the driver. Fig. 8 is a photograph that shows the relationship between the fiber array, laser array, driver IC, and the ceramic chip carrier. The temperature of the laser array is controlled via the copper submount by a Thermal Electric Cooler (TEC) and a heat sink. A controller circuit (daughter board) was designed and fabricated and is mounted on the transmitter mother board (Fig. 9). Unlike the laser array that requires a precise user-adjustable temperature to control wavelength, the driver array does not require a user-adjustable temperature. Consequently, there is no thermoelectric cooler within the heat dissipation path of the driver IC. In fact, it is noted that the GaAs driver chip is thermally managed entirely by only the side-mounted heat sink.

B. Ceramic Chip Carrier

The chip carrier can be seen in Fig. 8. The carrier provides fanout circuits between the laser driver array and the external solder tabs that are arranged in a butterfly configuration. Some of the pertinent characteristics of the ceramic carrier are a) the package dimensions are 2.1″ × 1.0″ × 0.035″, b) the substrate material is 95% aluminum oxide (Alumina), c) the metallization for the conductors is W/Ni/Au, d) the I/O pads are on a 25 mil pitch, e) a ribbon lead-frame is brazed to the I/O pads, and f) a two-tier wirebond pad topology (featuring 6 mil

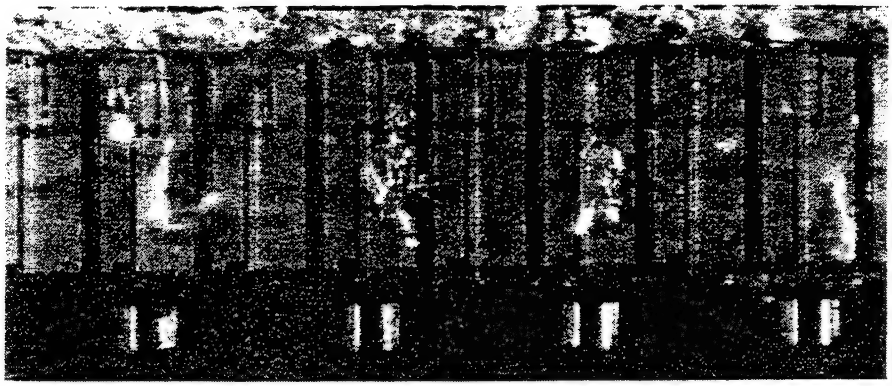


Fig. 7. A micrograph of the fiber array pigtail aligned with the laser array using a silicon V-grooved substrate.

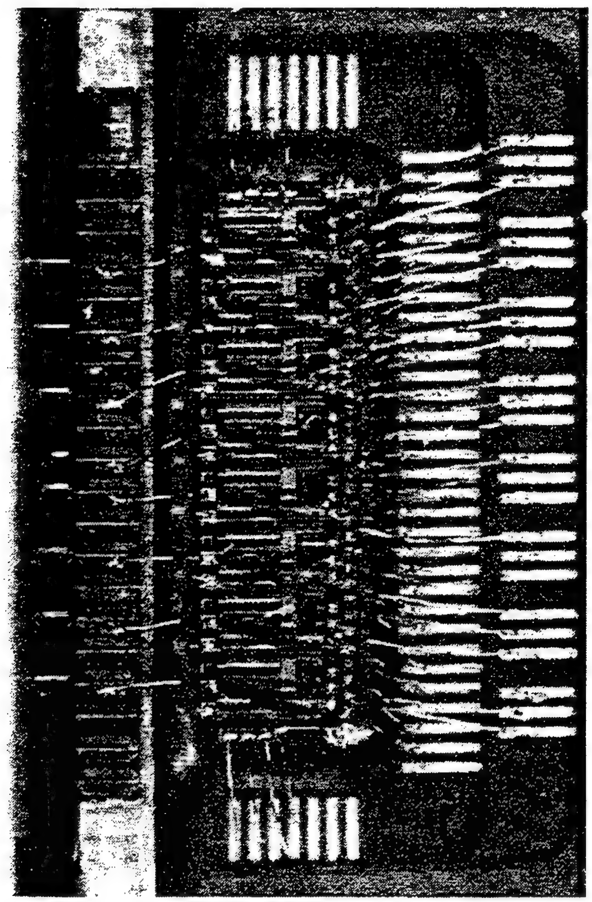


Fig. 8. Photograph of the relationship between the ceramic chip carrier, driver IC, laser array, and the fiber array.

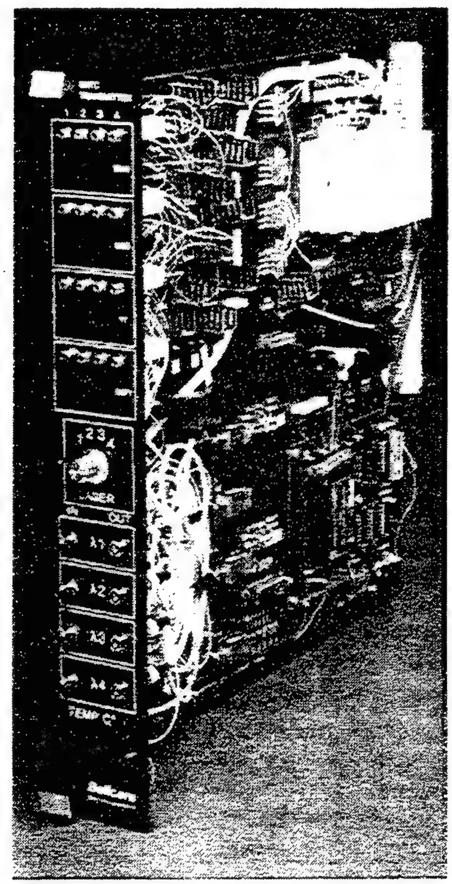


Fig. 9. Photograph of transmitter mother board showing laser module in top rear section of board and temperature controller daughter board in bottom rear section.

pitch, 3 mil-wide bond pads) is utilized. In addition, the carrier features seven metallization layers, six ceramic layers, 50 Ω conductors for the high-speed differential signals, and a layer #1 metallization that facilitates the mounting of decoupling capacitors.

The seven metal layers include the aforementioned pad layer for decoupling capacitor attachment, two layers used to route ideally dc levels such as bias voltages and other static levels, a composite dc power plane that is shared by V_{tt} (terminating resistor level) and V_{ee} (the most negative power supply voltage), the high-speed signal layer, and finally two ground planes. It is noted that the 50 Ω conductors are actually microstriplines that are generated by sandwiching the appropriate conductors between power planes, which are essentially ac grounds.

C. Thermal Management

A prudent combination of analytical techniques and finite element modeling were utilized for the thermal analysis of

TABLE V
OPTICAL CHARACTERISTICS OF TRANSMITTER MODULES. ALL LASERS WERE DRIVEN AT 60 mA AND ALL ARRAY WERE TEMPERATURE TUNED TO DESIGNED WAVELENGTHS

	Nominal wavelength (nm)	Laser wavelength offset (nm)	Power in fiber (dBm)	Coupling efficiency (dB)	Operating temperature (°C)
Module #1	1546	-0.3	-0.2	-4.5	20.7
	1550	-0.2	+1.1	-2.7	20.7
	1554	+0.4	-0.3	-3.7	20.7
	1558	-0.2	+0.7	-4.1	20.7
Module #2	1546	-0.1	+2.2	-2.1	16.9
	1550	+0.1	+1.3	-2.1	16.9
	1554	-0.1	+4.6	-2.3	16.9
	1558	+0.2	+2.0	-3.6	16.9
Module #3	1546	+0.2	+0.8	-3.7	15.4
	1550	+0.1	+0.4	-3.5	15.4
	1554	+0.1	+2.1	-4.5	15.4
	1558	-0.1	+2.9	-2.8	15.4
Module #4	1546	-0.1	-1.9	-6.8	20.9
	1550	+0.2	-0.1	-4.4	20.9
	1554	+0.1	-0.8	-3.0	20.9
	1558	+0.1	-0.3	-1.8	20.9

the module design. In this work, we considered numerous parameters including IC power dissipation levels, the effect of the TEC cold side temperature, the ambient temperature effects, and also the effect of insulation, i.e., varying film coefficients. The following results pertain to a local ambient temperature of 25 °C.

The analysis predicted that the temperature field of the laser array is independent of the local ambient temperature. The laser temperatures are dictated by the temperature boundary condition imposed by the TE cooler. This was seen by observing that the maximum laser temperature is consistently around 6.7 °C above the TE cooler's cold-side temperature. However, the situation for the driver chip is very different. It was determined that the temperature of the driver (which ranges from about 43.2 °C to 57.1 °C is a strong function of the local ambient temperature, but is essentially independent of the TE cooler's temperature. The maximum temperature of the GaAs chip was consistently shown to be about 17 to 18 °C above the local ambient temperature.

Thus, we have determined that, under the conditions anticipated, the temperatures of the lasers are both tunable and stable as required. This result has been corroborated by laboratory experiments using prototype laser arrays.

D. Module Performance

We have completed and delivered four transmitter modules required by the Phase 1 ONTC program. Table V summarizes the optical characteristics of four modules used in the testbed. Fig. 10 shows the transmitter output spectrum of the four-wavelength channels superimposed on the transmission spectrum of the filter characteristics of the cross-connect switch. Adjustment of the laser temperature to match the center wavelength of the WDM cross-connect filters has resulted in better than ±0.35 nm variation from the target wavelengths, with three modules less than ±0.2 nm. Small-signal modulation tests of the modules have shown transmission bandwidths of approximately 3 GHz at typical bias conditions. Fig. 11 displays the measured BER at 155 Mb/s for a typical module. The channel crosstalk penalty is negligible as can be seen in Fig. 11.

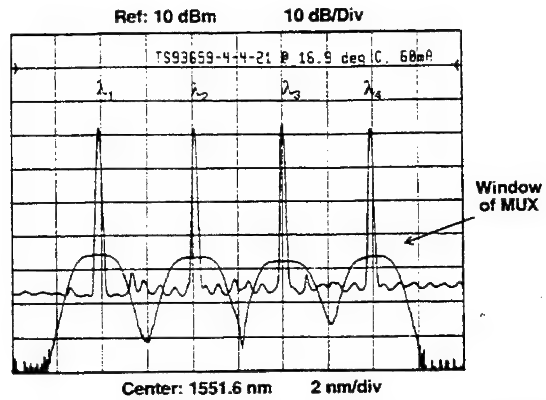


Fig. 10. The optical spectrum of the laser array transmitter superimposed on the transmission characteristics of the cross-connect switch.

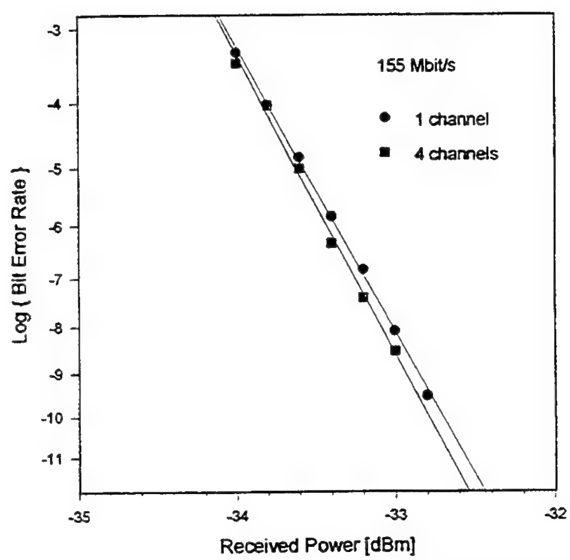


Fig. 11. Measured bit-error-rate at 155 Mbit/s of a typical multiwavelength transmitter module.

IV. CONCLUSION

Significant progress has been made recently in the design and fabrication of multiwavelength DFB laser arrays. Several DFB laser array transmitter experimental research prototypes have been successfully employed in a rearrangeable optical network testbed for the first time. Precise wavelength spacing and wavelength control have been achieved with reasonable yield for a four-wavelength array by the use of wavelength redundancy. The multiwavelength laser array has been demonstrated to be a viable light source for multiwavelength lightwave systems. It is expected that multiwavelength laser arrays can be cost competitive to that of single wavelength lasers when the yield of the array chip improves as required for large volume production.

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In 1963, he joined Bell Laboratories in Reading, PA, where he was engaged in the development of microwave semiconductor devices. He contributed to the deployment of the Bell System TD-2 and TD-3 microwave long-haul repeater systems. In 1966 he transferred to the Guided Wave Research Laboratory, Bell Laboratories, Crawford Hill, Holmdel, NJ. For the next two years, he conducted research on semiconductor millimeter wave upconverters, mixers, and IMPATT oscillators at 50 GHz for the first all-solid-state mm-wave repeater system. In 1968, his research interests turned to optoelectronic devices, including fast photodiodes, semiconductor lasers, and light-emitting diodes, for optical fiber telecommunication systems. His early theoretical and experimental work was on the short optical pulse generation based on Q-switching in semiconductor lasers. From 1970 to 1978, he designed the high-brightness AlGaAs light-emitting diodes for use in early optical fiber transmission experiments. His theoretical analysis and design of high power LED's published in 1978 has earned him world-wide recognition. Since 1978, his research focus has been in long wavelength photodetectors and semiconduct or lasers. His pioneering work on the InGaAs photodetectors

was the first report on the successful development of high sensitivity, long-wavelength photodiode that made it possible the development of the optical receivers at the long wavelength region. These efforts were extended to the deployment of the first commercial system at 1.3 μm wavelength in 1980. His interests have since focused on the fundamental understanding of the longitudinal mode characteristics of semiconductor lassers. His contribution to the single-frequency laser made it possible for the early high-speed lightwave systems experiments which paved the way for the rapid development of such systems in the late 1980's and in the 1990's. He was named the Director of Optoelectronic Technology Research of Bell Communications Research (Bellcore) in Red Bank, NJ, in 1984. His group pioneered the work on high-speed distributed feedback (DFB) lasers, semiconductor optical amplifiers, tunable distributed Bragg reflector lasers for coherent systems experiments. In the early 1990's, his group extended the work to include multiwavelength DFB laser arrays for optical networking. From 1992 to 1995, Bellcore led the Optical Network Technology Consortium that was funded by the Advanced Research Program Agency (ARPA). He is a key leader in this project to develop the multiwavelength laser array technology. In February 1995, several multiwavelength laser array transmitters were employed in the world's first rearrangeable multiwavelength all-optical network testbed demonstrated at OFC'95 in San Diego, CA. He became a Bellcore Research Fellow in 1995. He has published more than 190 papers and several book chapters. In addition, he has edited three books, and holds seven U.S. patents and six foreign patents on optical semiconductor devices.

Dr. Lee served as the Guest Editor, IEEE TRANSACTIONS ON ELECTRON DEVICES in 1983, and the Associate Editor of the JOURNAL OF LIGHTWAVE TECHNOLOGY from 1986 to 1988. He is now the Co-Editor-in-Chief, the *International Journal of High-Speed Electronics and Systems*. He has served on various Technical Program Committees, Advisory Committees, as Session Chair, Program Chair, and has been an invited speaker for various international conferences. He is the recipient of the Distinguished Technical Staff Award, Bell Laboratories, in 1983, and the President's Recognition Award, Bellcore, in 1994. He is a Fellow of the Optical Society of America and the Photonic Society of Chinese-Americans.

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He joined Bell Communications Research (Bellcore), Red Bank, NJ, as a Member of Technical Staff in 1985 and was promoted to Senior Scientist in January 1995 and to Director of Optoelectronic Integration Research in April 1995. His work has been in optoelectronic devices research for optical fiber communication systems including semiconductor lasers and optical amplifiers. He has lead a team to design and fabricate uncooled lasers, high-speed lasers, distributed-feedback lasers, wavelength tunable distributed-Bragg-reflector lasers, and multiwavelength distributed-feedback lasers arrays. He has also participated in several system demonstrations using his lasers and optical amplifiers, such as the subcarrier-multiplexed system, the coherent system, the wavelength-division-multiplexed system, and the Optical Network Technology Consortium (ONTC) testbed. His current interests and efforts are in strained-layer quantum-well devices, multiwavelength laser array integration and photonic integrated circuits. His group effort is to achieve optoelectronics integration vertically by material growth and laterally by integrated optics design and fabrication in support of Optical Networking projects and deliverables. During 1993 to 1995, he successfully led a team to develop four- and eight-wavelength DFB laser array prototypes for the ONTC reconfigurable multiwavelength optical network testbed funded by Advanced Research Project Agency (ARPA). Currently, he is responsible for developing the eight-wavelength modulator-integrated DFB laser array prototypes for local exchange testbed in the Multiwavelength Optical Networking Consortium (MONET) also funded by ARPA. He has authored of co-authored more than 80 journal papers (seven invited) and 110 conference papers (18 invited), and holds four U.S. Patents in the areas of optoelectronic devices and optical fiber communications.

Dr. Zah received the Bellcore Distinguished Member of Technical Staff Award in 1992 for innovative contributions to the applications of lightwave technology to advanced fiber networks and R&D 100 Award in 1994 for the uncooled AlGaInAs lasers for fiber-in-the-loop applications. He is a Fellow of the Optical Society of America and a member of the Phi Tau Phi Scholastic Honor Society and the Photonics Society of Chinese-Americans. He has served as a member of technical committees for IEDM'90, IEDM'91, LEOS'90, LEOS'91, LEOS'96, the 15th IEEE International Semiconductor Laser Conference, the 1991 and 1992 topical meeting on optical amplifiers and their application, the 1994 NSF Lightwave Technology panel, IPR'94, IPR'95, IPR'96, and CLEO'95, a session chair of the 9th and 12th IEEE/LEOS Semiconductor Laser Workshops on WDM light sources and tunable lasers, and photonic Integrated circuits for WDM applications, in 1992 and 1995, respectively, a symposium organizer of the 1994 OSA Annual Meeting on array devices for WDM networks, and an Associate Editor of the IEEE PHOTONICS TECHNOLOGY LETTERS since 1993.

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W. C. Young, photograph and biography not available at the time of publication.

B. Pathak, photograph and biography not available at the time of publication.

F. Favire, photograph and biography not available at the time of publication.

Paul S. D. Lin graduated from the physics department of the University of Chicago in 1972 specializing in field-emission electron beam instrumentation.

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Nicholas C. Andreadakis received the B.S. degree in physics from Franklin and Marshall College, Lancaster, PA, in 1962 and the M.S. and Ph.D. degrees in solid state physics from the University of Delaware in 1965 and 1968, respectively.

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Lyn Curtis was born in Roselle Park, NJ. He is a Member of Technical Staff in the Optical Network Element Group, Bellcore, Red Bank, NJ. Since 1975, he has been associated with the development of optical connectors and devices. He has received five patents and has co-authored several papers in this area.

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